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Cost and Performance Model for Evaluating Field Scale Granular Activated Carbon Systems

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A COST AND PERFORMANCE MODEL FOR EVALUATING FIELD SCALE GRANULAR ACTIVATED CARBON SYSTEMS

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16. ABSTRACT

Much has been written concerning the prediction of granular activated carbon (GAC) adsorption performance. Various types of models have been suggested to simulate the performance of GAC for single and bi-solute systems. EPA's drinking Water Research Division (DWRD) has approahced the problem of characterizing performance by initiating a series of field studies. Data from these studies are now becoming available for evaluation. In this paper data from DWRD's project with Jefferson Paris, Louisiana is analyzed. A model for characterizing breakthrough curves is developed. This model is merged with a series of cost equations to optimize the removal of TOC. Data from pilot columns is used to predict full scale performance and to find minimum cost solutions for field scale design. One of the most significant findings was that pilot columns predict the performance of full scale systems very well.

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A COST AND PERFORMANCE MODEL FOR EVALUATING FIELD SCALE GRANULAR ACTIVATED CARBON SYSTEMS

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Much has been written concerning the prediction of granular activated carbon (GAC) adsorption performance. Frequently models are purposed to simulate the performance of GAC systems for single and bi-solute systems. Often equilibrium expressions and mass transfer constants are estimated or calculated for specific adsorbate-GAC combinations. Mass transfer constants determined by this method may then be extrapolated to predict full scale GAC adsorber performance.[1,2,3,4]

EPA's Drinking Water Research Division initiated a series of field studies to evaluate and characterize the performance of GAC. These field scale systems consisted of units that are close to modular size for a water treatment plant. Eight utilities who participated in these studies are: Cincinnati, Ohio; Manchester, New Hampshire; Evansville, Indiana; Jefferson Parish, Louisiana; Miami, Florida; Huntington, West Virginia; Beaver Falls, Pennsylvania; and Passaic, New Jersey.

Data from these projects are now becoming available for analysis. Information from the Jefferson Parish project will be analyzed using an empirical model that was developed for characterizing Total Organic Carbon (TOC) breakthrough curves from granular activated carbon (GAC). The model was applied to GAC pilot column data and extrapolations from pilot column and model data was applied to scale-up projections. A model based on best current cost estimates of "in place" technology combined with the performance data is used to estimate minimum cost design for full scale GAC systems.

FIELD SCALE SYSTEM

The Jefferson Parish study is ongoing and consists of essentially two phases.[5] The first portion of the study dealt with conversion of individual sand filters into a filter adsorber and an adsorber. The second phase of the operation consists of three contactors each with a design flow of 0.044 m^3/sec (1 mgd), and an empty bed contact time of 20 min. The regeneration system is an infrared furnace with a capacity of 97.5 kg/hr (215 lbs/hr). Data from the first phase of the Jefferson Parish project was used in this analysis.

JEFFERSON PARISH

The conventional treatment plant at Jefferson Parish pumps raw source water from the Mississippi River (Figure 1). Total design flow of this plant is 3.1 m^3/sec (70 mgd) incorporating four separate smaller treatment plants with an average flow of about 2.4 m3/sec (55 mgd). Only one

of the smaller plants within the treatment complex was used for the research effort at a design flow of 0.4 m^3/sec (10 mgd). Potassium permanganage (0.5 - 1.0 mg/L) is added for taste and odor control as the first treatment step. A cationic polyelectrolyte [diallyldimethyl diammonium chloride (0.5 - 8.0 mg/L)] is added as the primary coagulant. Lime (7 - 10 mg/L) is continuously fed for pH adjustment to 8.0 - 8.3. After the precipitators, chlorine and ammonia are added in a ratio of 3:1 for chloramine disinfection before sand filtration. Monochloramine concentrations prior to the adsorbers and filter adsorbers ranged from 1.4 - 1.7 mg/L.

Two sand filters were converted to granular activated carbon beds for evaluation. One was designed as a filter adsorber because it served a dual purpose of removing filterable turbidity and adsorption of dissolved organic compounds. This filter received clarified chloraminated water. Media for the filter adsorber consisted of a 15.2 cm (6 in) layer of sand covered by a 61 cm (24 in) of GAC in two modes of operation. During the other modes, the sand layer was removed so that the filter adsorber contained 76.2 cm (30 in) of GAC.

The second filter was utilized as an adsorber for post-sand filter adsorption. This filter consisted of 76.2 cm (30 in) of the same type of GAC used in the filter adsorber. The average hydraulic loading for both of these filters was 2.2 m/hr (0.9 gpm/ft^2) with corresponding EBCTs of 17.5 and 20.4 min, respectively, for the filter adsorber and adsorber.

Pilot Columns

Two GAC pilot columns were operated under the same conditions, in parallel with their full-scale filter adsorber and adsorber counterparts. These pilot columns were given the designations of adsorber simulator and filter adsorber simulator. Each column received influent water from the same sources and at hydraulic loadings that yielded the same relative EBCT's as the full scale units.

The pilot column simulators were constructed of glass 7.6 cm (3 in) in diameter and 1.5 meters (5 ft) in height and contained 76.2 cm (30 in) of GAC on top of 15.2 cm (6 in) of support gravel. Also, four other GAC pilot columns were operated in series at a flow rate of 0.76 L/min (0.2 gal/min) to simulate the effect of 10, 20, 30, and 40 minutes of EBCT on post-filtration contactors. These glass columns were 10.2 cm (4 in) in diameter, 1.8 meters (6 ft) in height and contained 91.4 cm (36 in) of GAC on top of 15.2 cm (6 in) support gravel. The influent water for these pilot post-filtration contactors was the same as that for the adsorber simulator column. Data from these columns was used in a subsequent analysis.

PERFORMANCE MODEL

The performance model developed for this analysis is based on the use of the generalized logistic function as follow:[6]

$$C_t^{n-1} = [C_i^{n-1}/(1 + Ae^{-rt})] \qquad (1)$$

where

C_t = effluent contamination concentration
C_i = influent contamination concentration

A,r = constants
t = time in days
n = inverse of the Fruendlich isotherm slope

Given an effluent history and isotherm information (value for n), the values of A and r can be determined.

A complete derivation of this model is given elsewhere.[7]

APPLICATION OF MODEL TO SYSTEM

An isotherm relationship was estimated based on effluent histories taken from a series of pilot and field scale contactor experiments at the Jefferson Parish site. The equilibrium points at column exhaustion were used to calculate the Freundlich isotherm (7 points).

The Freundlich isotherm equation is:

$$q = 8.21\ C_e^{0.316} \qquad (r^2 = 0.70) \qquad (2)$$

where

q = mg/g of TOC adsorbed
C_e = equilibrium concentration in mg/L of TOC

The first step in this analysis was be to demonstrate that the pilot absorber replicates the full scale adsorber. To establish this relationship equation (1) was "fit", using regression techniques,to the effluent history data from the pilot adsorber. Figure 2 shows the best fit equation (dotted line) as estimated from the pilot adsorber data. To accomplish this, equation (1) was reformatted as follows:

$$\ln [(C_i/C_t)^{n-1} - 1] = \ln A - rt \qquad (3)$$

In equation (3), n = 3.16 from equation (2).

The values for "A" and "r" can be estimated from the best fit of equation (3) to the column effluent data assuming:

C_i = column influent at time t
C_t = column effluent at time t

This best fit equation was also plotted against the effluent history from the full scale adsorber in Figure 3. As can be seen, the pilot column equation replicates the adsorber data well.

The best fit equation (dotted line) as shown in Figures 2 and 3 is as follows:

$$C_t = [C_i^{2.16}/(1 + 80.25e^{-0.029t})]^{0.461} \qquad (4)$$

SIMULATION OF FULL SCALE SYSTEM

To simulate a full scale system, data from the four pilot columns with empty bed contact times (EBCT) of 10, 20, 30, and 40 min respectively were used. Figure 4 shows the influent and effluent histories along with the best fit lines for these four pilot columns. The best fit equations are as follows:

$$C_{10} = [C_i^{2.16}/(1 + 16.25e^{-0.026t})]^{0.461} \quad (5)$$
$$C_{20} = [C_i^{2.16}/(1 + 51.07e^{-0.024t})]^{0.461} \quad (6)$$
$$C_{30} = [C_i^{2.16}/(1 + 61.67e^{-0.016t})]^{0.461} \quad (7)$$
$$C_{40} = [C_i^{2.16}/(1 + 118.28e^{-0.015t})]^{0.461} \quad (8)$$

As can be seen from equations (5) through (8) the values for A and r (equation 3) vary with EBCT. Plotting A and r versus EBCT yields Figures 5 and 6.

By choosing EBCT's below 10 min and above 40 min on the lines in Figures 5 and 6 values for A and r can be selected to extrapolate equation (1). For example, by choosing an EBCT of 5 min, the values of A = 6.1 and r = 0.030 are selected using Figures 5 and 6. These values can be used to provide an estimated breakthrough curve for 5 min EBCT. Extrapolation was used because there is no data available for shorter or longer values of EBCT. A preferable approach would be to have actual column experiments for a wider range of EBCT's. The problems and limitations of using extrapolated data is discussed later. Table 1 contains the parameters for EBCT's of 1, 5, 10, 20, 30, 40, 50, 60, 70, and 80 min.

Solving each of the resulting equations for breakthrough times at levels of 0.5, 0.75, 1.0, 1.5 and 2.0 mg/l yields the results in Table 2. These values are based on the assumption of a constant influent value of C_i = 3.5 mg/l.

The values in Table 2 can be converted to a carbon use rate of kg/day (lbs/day) for various effluent targets by estimating the intersection of the breakthrough target with the breakthrough curve [weight per column was 1.28 kg (7.85 lbs)] This intersection yields a breakthrough period which when divided into the equivalent weight for EBCT yields a carbon use rate.

Table 3 contains the use rates in lbs/day for various EBCT and target levels associated with the pilot columns and the extrapolated values.

PROJECTION TO FULL SCALE SYSTEM

To illustrate the application of these data to a full-scale configuration the following conditions will be assumed: a TOC influent concentration of 3.5 mg/l; a design capacity of 0.26 m^3/sec (70 MGD); of an average flow of 0.21 m^3/sec (55 MGD); twenty contactors, with an average cross section of 9.91 m (32.5 feet) x 9.91 m (32.5 feet); and a hydraulic loading of 0.9 m/hr (2.3 gpm/ft^2) for a full scale system design. No attempt was made to estimate the effect of an increased loading rate on breakthrough. Using these data and the pilot column use rate data from Table 3 the GAC use rates in lbs/day for the full scale system were calculated as shown in Table 4.

DEVELOPMENT OF COST MODEL

The concept behind the cost model was to develop regression equations based on previously developed design data and "in place" technology.[8] The equations used for this study are based on the most current data available and are as follows:

Concrete Gravity Contactors

$$CCC = (30{,}000 + 1967.27\ VOL^{0.66})\ (CCI/2850.7) \quad (9)$$
$$CBP = (32{,}685 + 15.14\ GPM^{0.93})\ (CCI/2850.7) \quad (10)$$

$$CCS = (14{,}106 + 6.69\ CUFT^{1.10})\ (CCI/2850.7) \quad (11)$$
$$GC = (UGAC)\ (GACAMT)^{.04}\ (QTY)^{0.96} \quad (12)$$
$$CE = (5)\ (TAREA) + (15{,}152 + 350\ TAREA^{0.92}) \quad (13)$$
$$CL = (701 + 3.25\ TAREA^{0.84}) \quad (14)$$
$$CM = (375 + 16.32\ TAREA^{0.75})\ (PPI/199.7) \quad (15)$$

Fluid Bed Reactivation

$$RCC = (718836 + 5633.76\ DSIZE^{0.49})\ (CCI/2850.7) \quad (16)$$
$$RE = 43.8\ DSIZE \quad (17)$$
$$RL = 10690 + 0.175\ DSIZE^{1.01} \quad (18)$$
$$RM = (7232 + 385.19\ DSIZE^{0.35})\ (PPI/199.7) \quad (19)$$
$$RF = 799. + 7.53\ DSIZE^{1.01} \quad (20)$$

where

CCC = concrete gravity contractor construction cost ($)
VOL = total effective GAC volume, all contactors combined (ft^3)
CCI = construction cost index ENR base year 1913
CBP = construction cost for backwash pumping ($)
GPM = total capacity of overall system (gpm)
CCS = construction cost of carbon storage ($)
CUFT = total effective GAC storage volume (ft^3)
GC = cost of GAC ($); used for estimating initial GAC, virgin replacement or make-up
UGAC = unit price of GAC at "GACAMT" per manufacturer's quote ($/lb)
GACAMT= quantity of carbon on which "UGAC" is based per manufacturer's quote (lbs)
QTY = quantity of GAC being cost estimated (lbs)
CE = contactor O&M electrical usage (kwh/year)
TAREA = overall combined cross-sectional area of all contactors (ft^2)
CL = contactors O&M labor usage (manhours/year) based on 100% utilization, adjust accordingly
CM = contactors O&M maintenance material cost ($/yr)
PPI = producers price index for finished goods
RCC = fluid bed reactivation construction cost ($)
DSIZE = design capacity of an individual reactivator (lbs/day)
RE = reactivation O&M electrical usage (kwh/year), based on 100% utilization
RL = reactivation O&M labor usage (manhours/year), based on 100% utilization
RM = reactivation maintenance material cost ($/yr), based on 100% utilization
RF = reactivation operation fuel oil usage (gal/yr), based on 100% utilization

In using these equations the following items must be considered:

1. Construction cost functions exclude engineering fees, overhead, profit, interest during construction, and special site specific considerations. These must be added separately.

2. Labor for on-site GAC transport is 0.844 manhours/kg (0.383 manhours/100 lbs) of carbon transferred.

3. Water for on-site GAC trasport is 16.7 L/kg (2 gal/lb) of carbon tranferred.

4. Water for reactivation process is 175.3 L/g (21 gal/lb) of GAC reactivated.

The parameters assumed in the cost analyses are shown in Table 5.

The costs for various full scale systems based on the previously assumed conditions are given in Table 6.

Figure 7 is a plot of the costs in Table 6 versus Empty Bed Contact Time for each breakthrough target. This figure shows a minimum cost point for all of the breakthrough levels with the exception of 0.5 mg/L. Fortunately the minimum cost for most of the breakthrough targets falls in the range of EBCT provided by the pilot columns. As one moves further and further away from the span of actual data, the performance and cost data become increasingly unreliable. This analysis points up the need to test a wide range of EBCT's when using pilot column simulation. Figure 8 shows a plot of percent removal versus cost of removal for TOC. The TOC removal and cost is fairly linear up to the 70% removal level.

SUMMARY AND CONCLUSIONS

Modeling techniques provide a means of systematic comparison and extrapolations of GAC performance in the form of breakthrough curves. The emperical techniques used in this paper are simple and easy to extrapolate, although more sophisticated techniques are available. Using a combination of pilot columns and modeling the authors were able to replicate field scale performance. Scale up of use rates was used to predict full scale system costs. Optimum designs were developed for a range of TOC target levels. This effort demonstrates the usefulness of a combination of modeling and pilot columns for full scale predictions.

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TABLE 1. PARAMETERS FOR GENERALIZED LOGISTIC FUNCTION

EBCT (min)	A	r
1	0.70	0.076
5	6.10	0.030
10	17.01	0.026
20	43.37	0.024
30	61.67	0.016
40	118.28	0.015
50	150.00	0.014
60	175.00	0.013
70	230.00	0.012
80	300.00	0.011

TABLE 2. BREAKTHROUGH TIME IN DAYS

	Level in mg/L				
EBCT (min.)	0.5	0.75	1.0	1.5	2.0
1	-	-	-	-	-
5	-	-	-	5.1	31.8
10	-	-	5.8	43.5	74.3
20	-	26.8	54.0	95.0	128.3
30	-	51.9	92.8	154.2	204.2
40	39.0	98.7	142.4	207.9	261.3
50	58.9	122.8	169.6	239.7	296.9
60	75.2	144.1	194.5	270.0	331.6
70	104.3	178.8	233.4	315.3	382.0
80	137.9	219.2	278.8	368.1	440.9

TABLE 3. CARBON USE RATE IN LBS/DAY FOR PILOT COLUMNS*

EBCT (min)	TOC Target Level				
	0.5	0.75	1.0	1.5	2.0
1	-	-	-	-	-
5	-	-	-	0.77	0.12
10	-	-	1.35	0.18	0.11
20	-	0.59	0.29	0.17	0.12
30	-	0.45	0.25	0.15	0.12
40	0.90	0.32	0.22	0.15	0.12
50	0.67	0.32	0.23	0.16	0.13
60	0.63	0.32	0.24	0.17	0.14
70	0.53	0.31	0.24	0.17	0.14
80	0.46	0.29	0.23	0.17	0.14

*To convert from lbs/day to kg/day multiply by 0.4535.

TABLE 4. FULL SCALE GAC USE RATES (LBS/DAY)*

EBCT (min)	TOC TARGET LEVEL (mg/L)				
	.5	.75	1.0	1.5	2.0
5	-	-	-	191,142	30,655
10	-	-	336,145	44,819	26,240
20	-	145,496	72,209	41,045	30,392
30	-	112,696	63,027	37,931	28,643
40	199,963	79,013	54,765	37,511	29,845
50	165,505	79,383	57,478	40,668	32,833
60	155,557	81,179	60,143	43,325	35,277
70	130,849	76,328	58,473	43,284	35,726
80	113,105	71,155	55,944	42,372	35,376

*To convert from lbs/day to kg/day multiply by 0.4535.

TABLE 5. PARAMETERS USED IN COST ESTIMATES

Parameter	Value
GAC Unit Price	154 ¢/kg @ 18,140 kg (70¢/lb @40,000 lbs)
Capital recovery interest rate	10%
Capital recovery period	20 yrs
Construction overhead and profit	10%
Interest during construction	8%
Construction engineering fees	15%
ENR 1913 Construction Cost Index (1986)	4229
Producers price index (1986)	294
Labor rate	$10/hr
Electric rate	$0.07/kwh
Fuel oil price	1.98 $/kg ($0.90/gal)
Process water rate	1.10 $/kg ($0.50/gal)
GAC bulk density	480.7 kg/m^3 (30 lb/ft^3)
GAC loss rate from reactivation and handling	11%
Reactivation uptime factor	75%

TABLE 6. JEFFERSON PARISH FULL SCALE COST ESTIMATES (¢/1000 gal)*

	TOC Target Level (mg/L)				
EBCT	.5	.75	1.0	1.5	2.0
5	-	-	-	68.2	17.3
10	-	-	114.2	24.4	17.8
20	-	57.5	33.7	26.1	21.5
30	-	49.9	33.8	27.7	23.4
40	78.9	41.9	34.0	29.7	25.8
50	70.7	44.0	36.6	32.5	28.5
60	68.2	46.3	39.2	35.0	31.0
70	62.0	46.9	40.6	36.8	33.0
80	59.6	47.5	41.7	38.4	34.6

*To convert from ¢/1000 gal to ¢/m^3 multiply by 2.64.

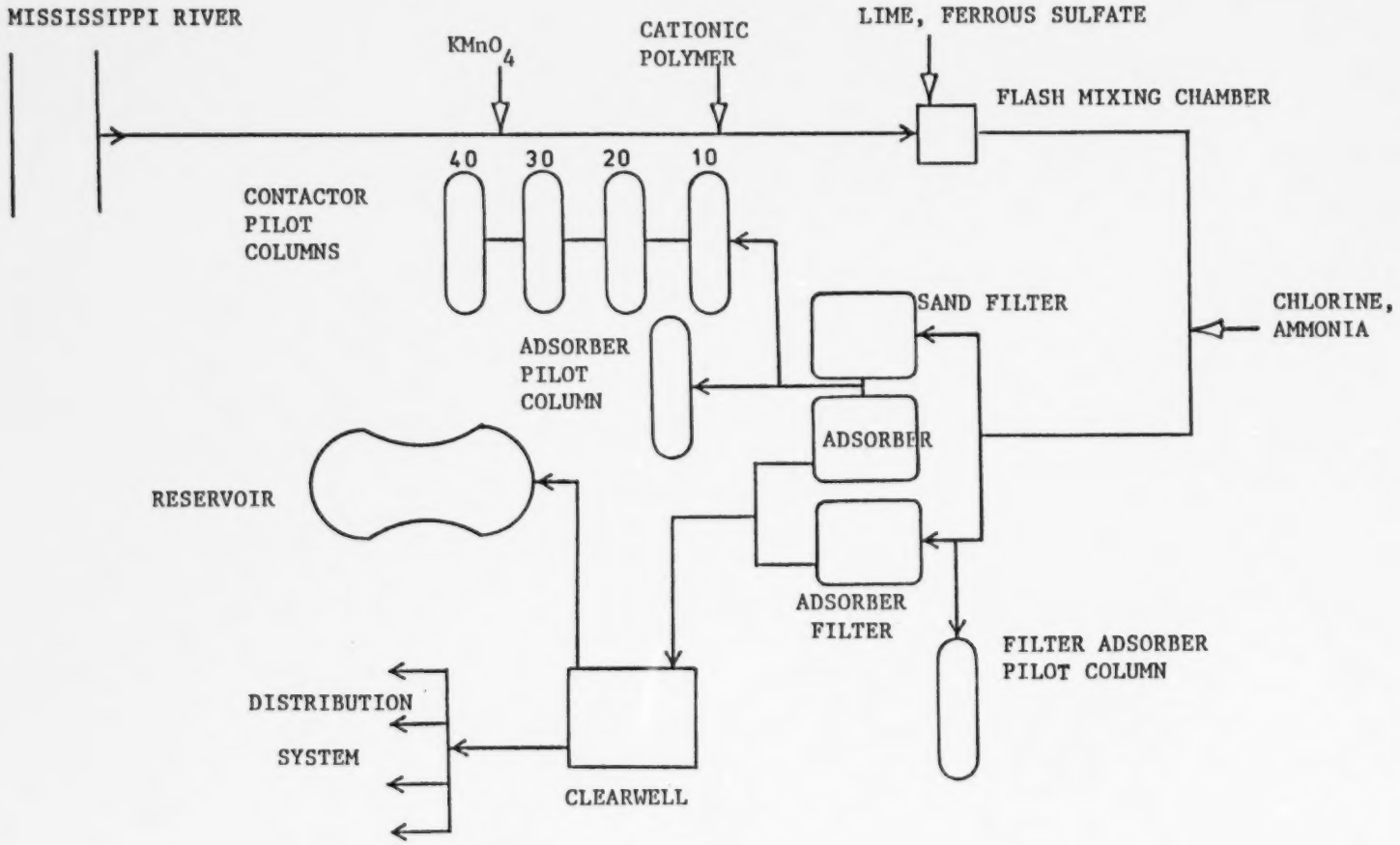

FIGURE 1. FULL-SCALE FILTER AND PILOT COLUMN FLOW CHART FOR JEFFERSON PARISH, LA.

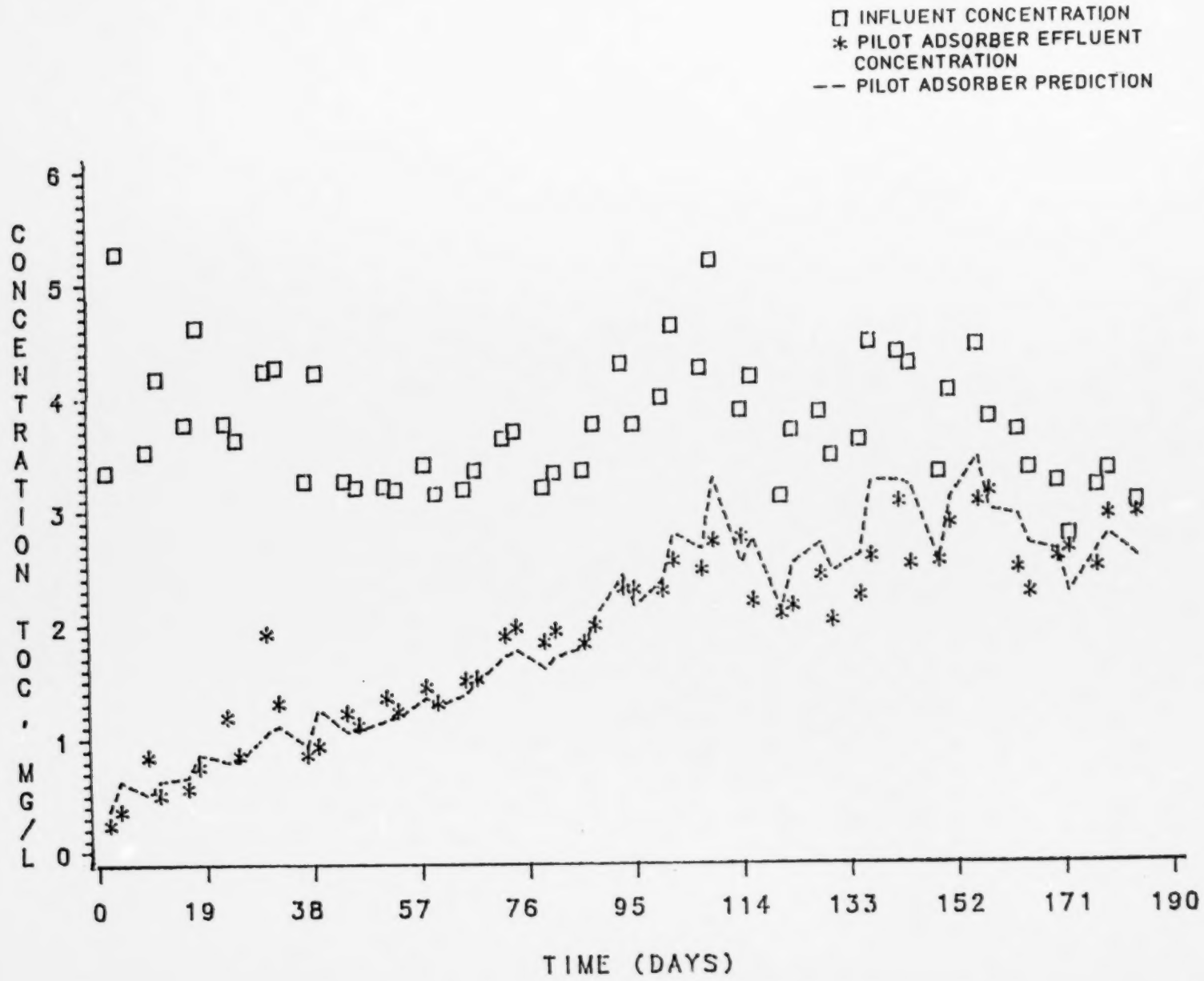

FIGURE 2. COMPARISON OF PREDICTED AND ACTUAL PILOT ADSORBER TOC CONCENTRATION - JEFFERSON PARISH, LA

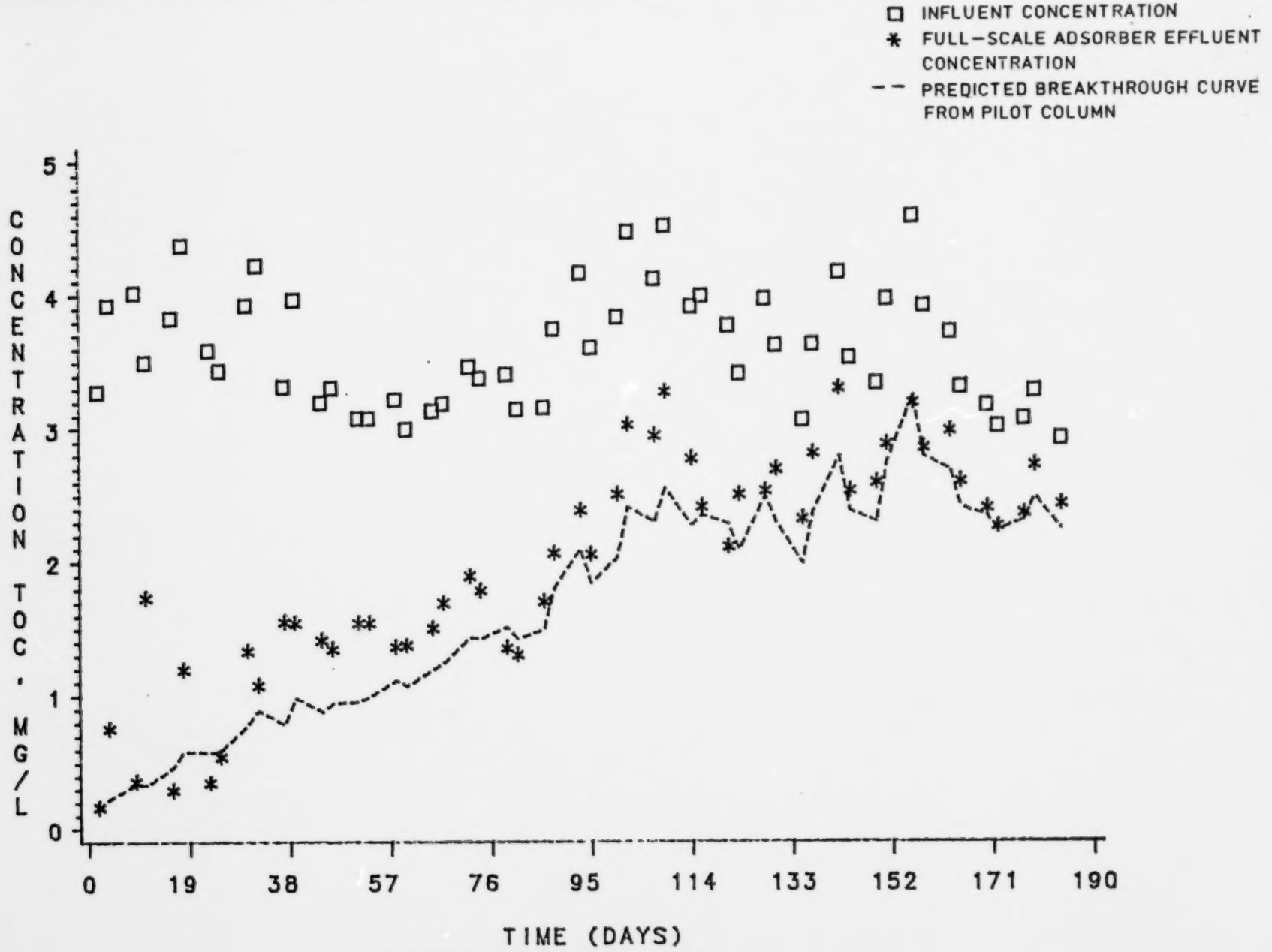

FIGURE 3. COMPARISON OF FULL-SCALE ADSORBER AND PILOT COLUMN PREDICTION OF FULL SCALE ADSORBER CONCENTRATION - JEFFERSON PARISH, LA

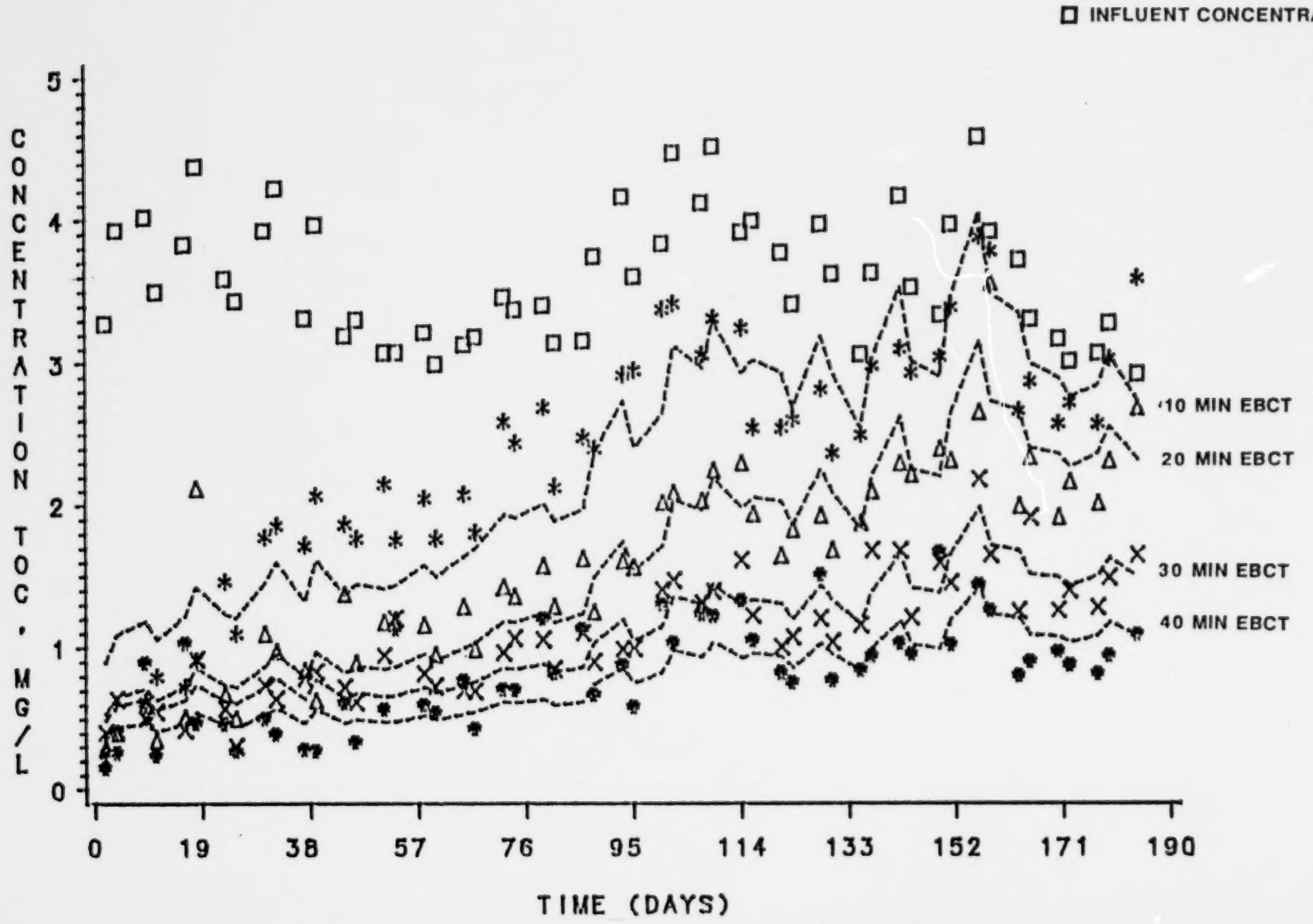

FIGURE 4. BEST FIT LINES FOR 10, 20, 30 AND 40 MIN EBCT'S FROM PILOT COLUMN - JEFFERSON PARISH

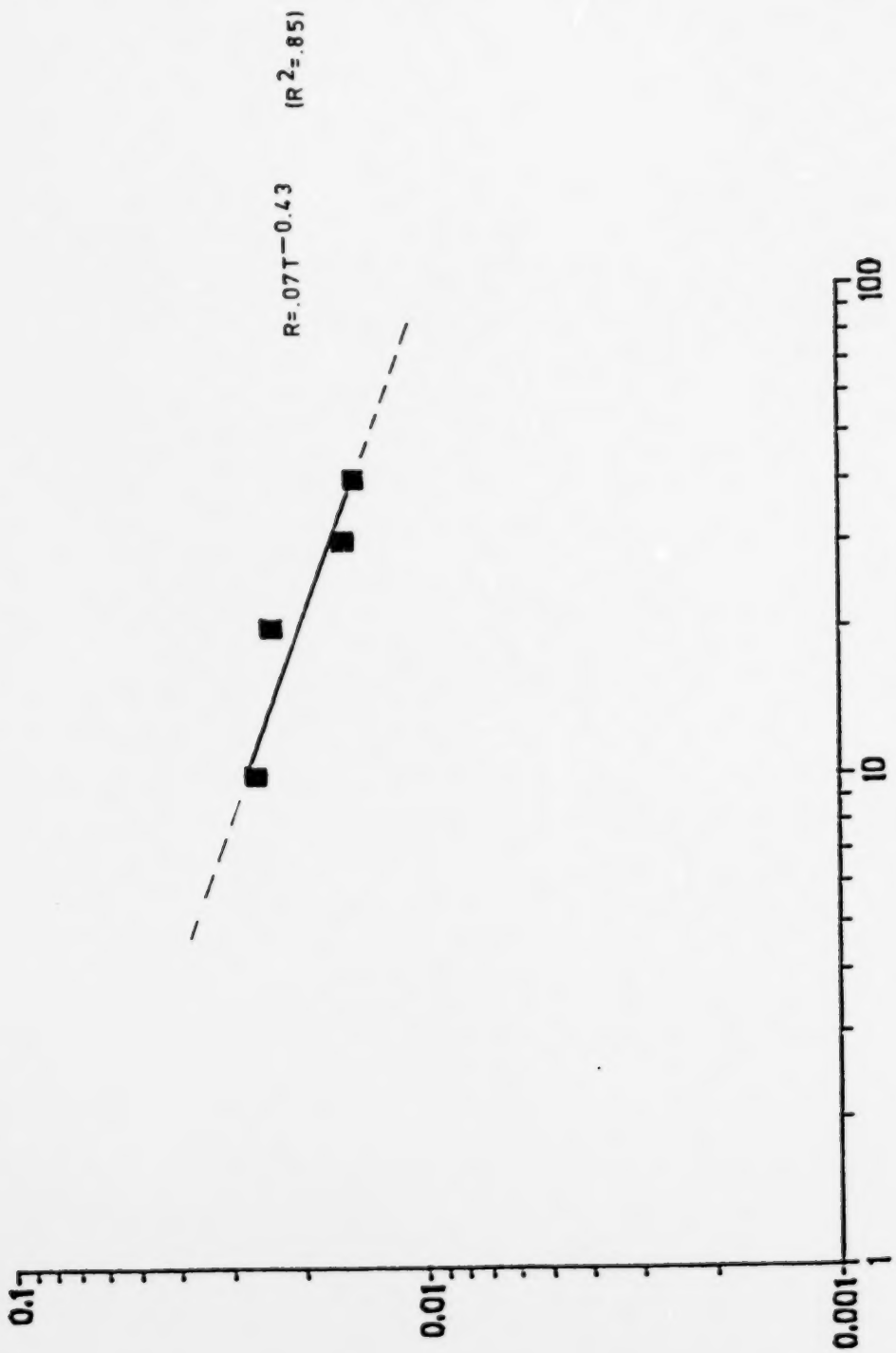

FIGURE 5. NATURAL LOG OF R VERSUS NATURAL LOG OF EBCT

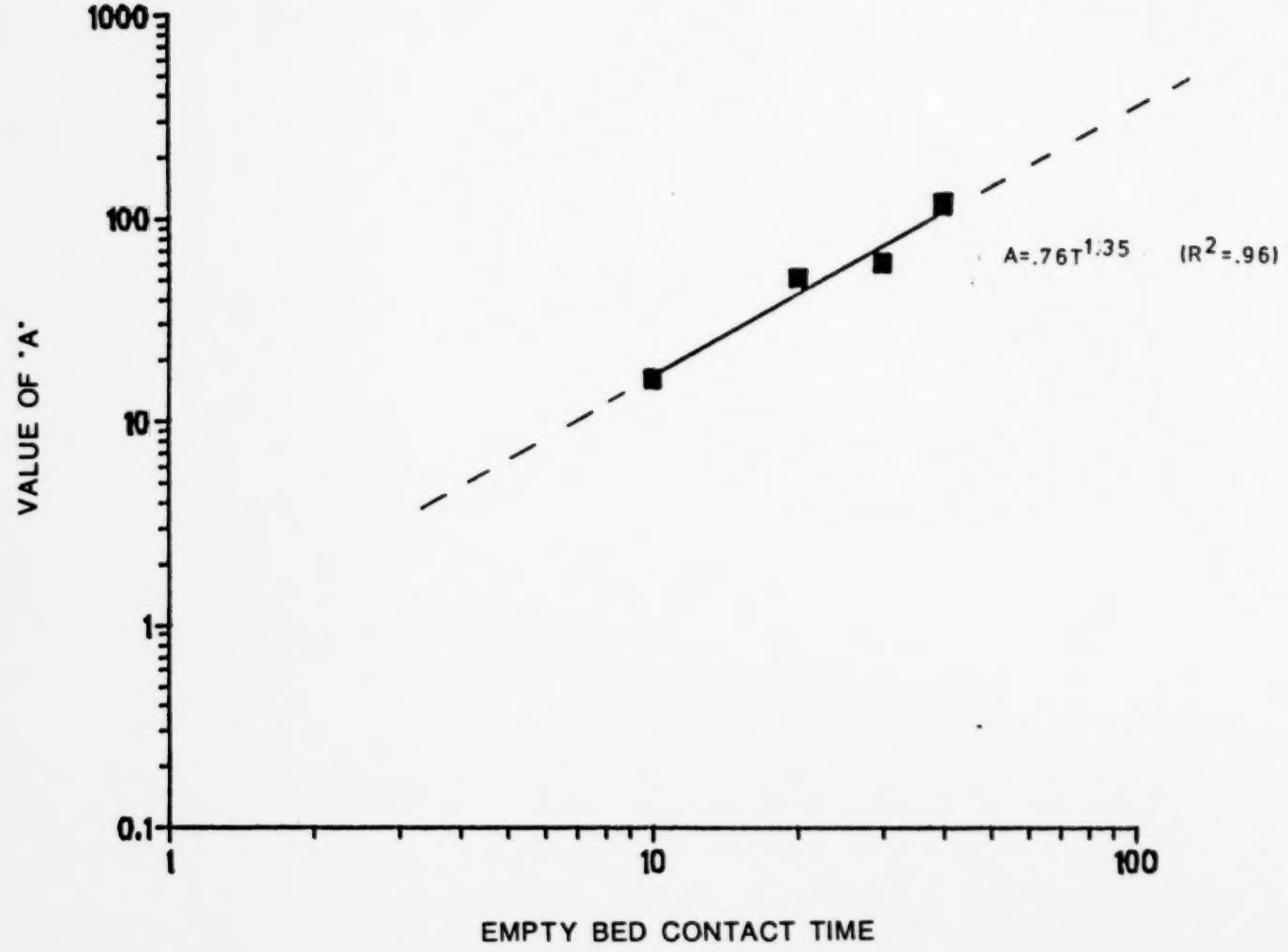

FIGURE 6. NATURAL LOG OF A VERSUS NATURAL LOG OF EBCT

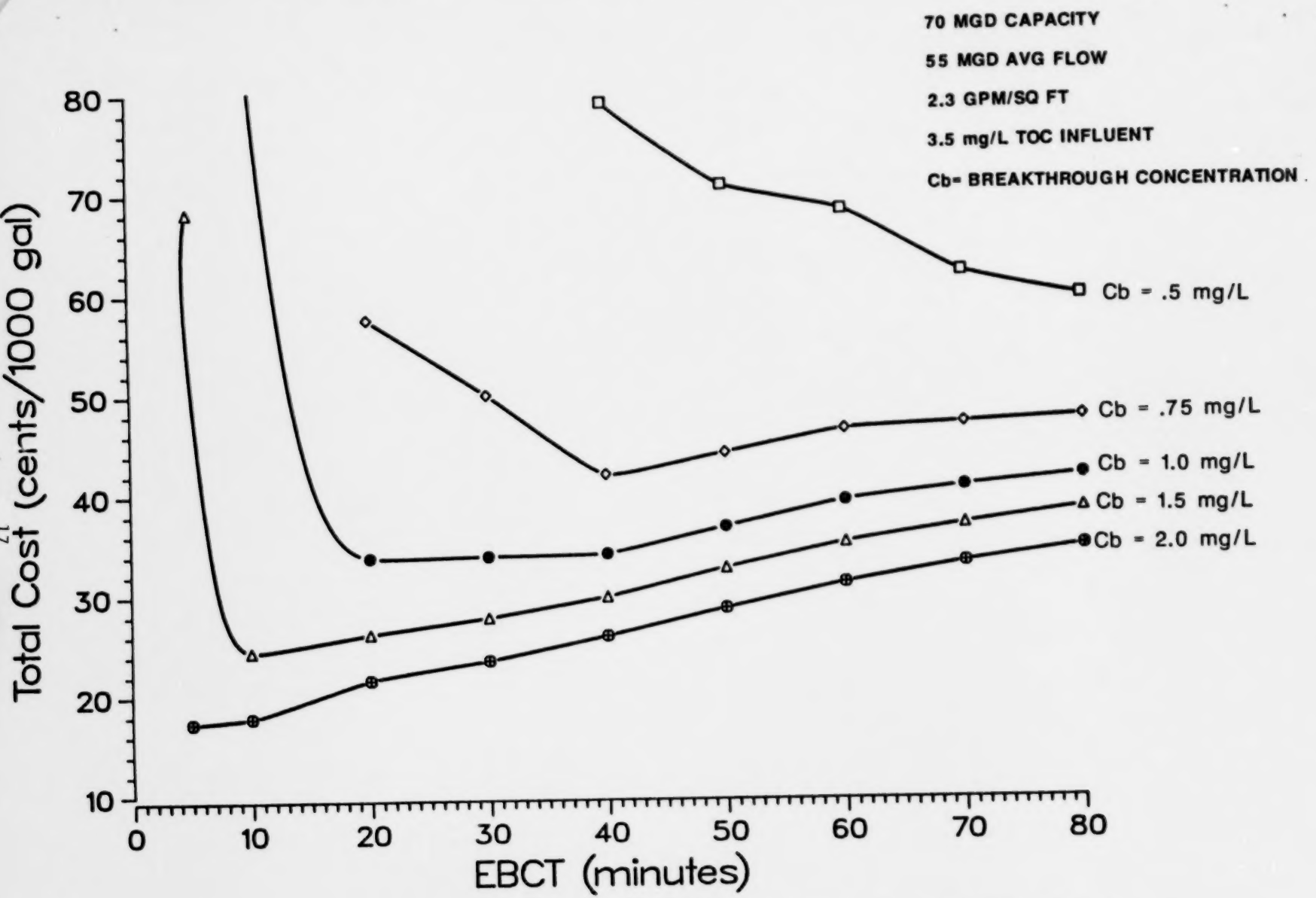

FIGURE 7. FULL-SCALE COST ESTIMATES VERSUS EMPTY BED CONTACT TIME AT VARIOUS BREAKTHROUGH TARGETS

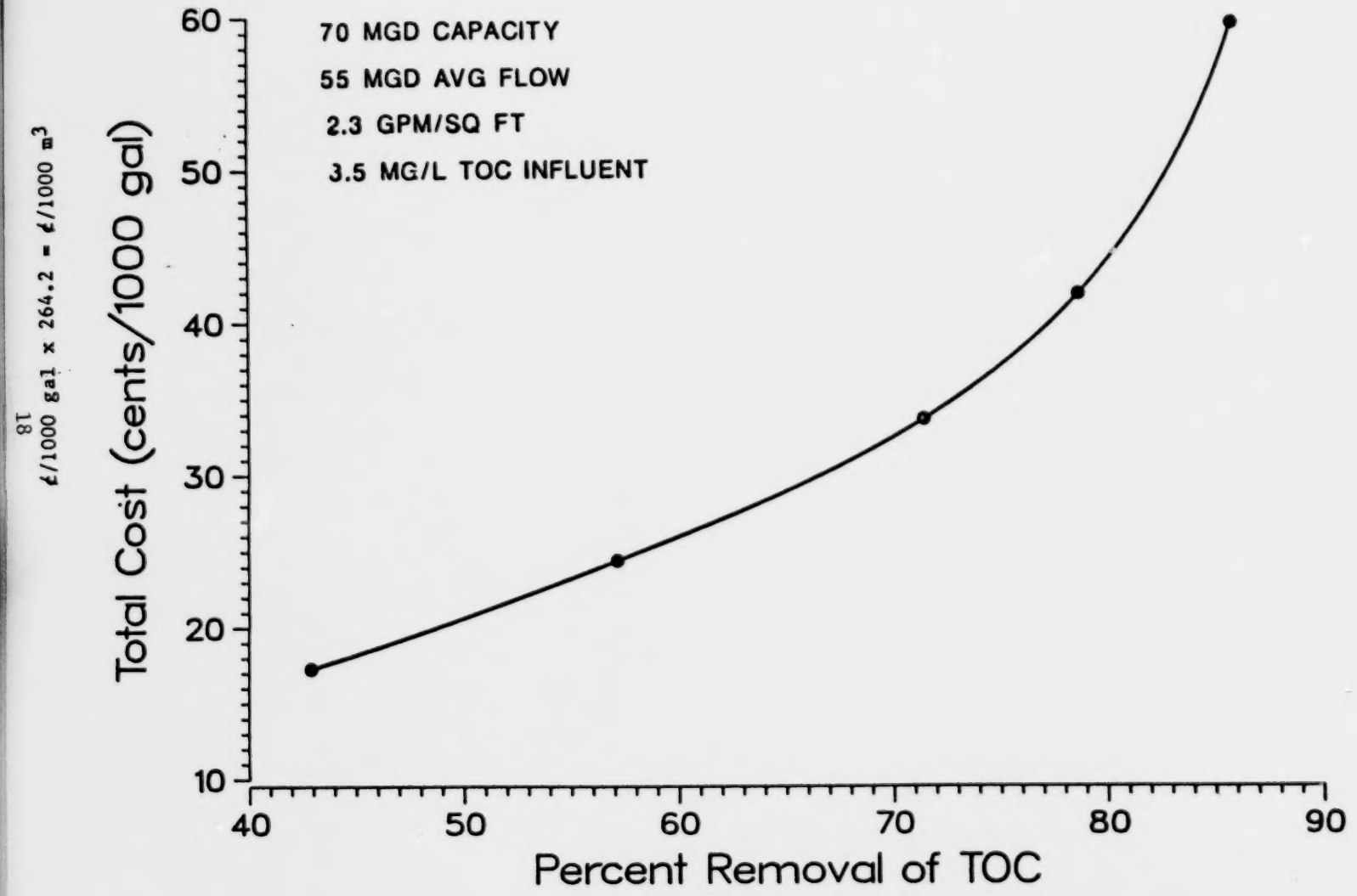

FIGURE 8. MINIMUM COST OF TOC REMOVAL VERSUS PERCENT REMOVAL